Effects of Multi-directionality on Pedestrian Flow Characteristics

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Abstract
In design and analysis, standard references assume the pedestrian flow as unidirectional. In reality however, pedestrian flow is usually bi-directional. The main question pursued in this paper is that whether the main characteristics of pedestrian flow the same under uni- and bi-directional conditions. In order to achieve this goal, effect of bi-directional stream is investigated on behavior and main parameters of pedestrian flow. Part of the data for the research was collected via controlled experiments and another part was videotaped from Isfahan walkways. It is shown that under bi-directional condition, mean speed of pedestrians is significantly more than the similar condition under uni-directional regime. Moreover, relative discrepancy between pedestrian speeds in two types of flow becomes evident in densities higher than 0.6 person/m^2. Speed of pedestrians in the majority and minority group were recorded and there from it was concluded that the density in the vicinity of a person has a greater effect on her walking speed compared to the opposite flow. In order to avoid colliding to opposite flow, pedestrians try to follow the preceding person and therefor lines are established within the crowd. Fundamental diagrams are also derived for different directional ration. As the index of disorder, entropy was calculated for uni- and bidirectional flows. It was concluded that entropy was lower for bidirectional flows which means that order improves under bidirectional regime of flow. This is in accordance with less freedom of movement under bidirectional regime.

Keywords: Fundamental diagram, pedestrian flow, bidirectional flow, traversing lines, entropy.

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1. Introduction

Promotion of walking in urban areas requires understanding of the characteristics of the pedestrian flow. Main design manuals including the Highway Capacity Manual (HCM) present tables for determination of the level of service in pedestrian facilities. In HCM, calculations are based upon the number and speed of pedestrians and analysis is not sensitive to the direction of flow. On the other hand, various studies are being carried out on multidirectional flow and its difference with unidirectional pedestrian flow. Results of these studies are not ubiquitous. Therefore, a research based on local data might shed light on the effect of multidirectionality in pedestrian facilities within Iranian environment.

Bandini et al. conducted several experiments under densities ranging from 0.6 to as high as 10 person/m^2 to derive fundamental diagrams of pedestrian flow. They also simulated the pedestrian flow using cellular automata framework for both uni and bidirectional cases and observed significant differences among them [Bandini, Mondini and Vizzari, 2014]. Kretz et al. investigated pedestrian flow in a corridor and concluded that compared to similar unidirectional flow, bidirectional flow has lower speed and the speed drop is more severe in the minority group. In other words, the minority is more affected by the opposite flow. They also found that under bidirectional regime, the sum of flows is more than the flow of unidirectional regime [Kretz et al., 2008]. Contrary to Kretz et al., Zhang et al. found that only in densities higher than 1 person/m^2 the fundamental diagram of uni and bidirectional flows are different. They also observed that the flow rate of unidirectional flow was significantly higher than flow rate of similar bidirectional flow [Zhanf et al., 2012].

Flötteröd and Lämmel used cellular automata to describe the bidirectional pedestrian flow. Using real data they concluded that the speed of the pedestrian is more affected by the density of the same direction rather than the opposite direction [Flötteröd and Lämmel, 2015]. This conclusion is in contrast with the conclusion of Kretz et al.

Blue and Adler investigated three phenomena in bidirectional pedestrian flows. The first, named separation is the situation in which each direction of flow passes by the other one. The second, named scattered flow is the situation in which pedestrians find their way within the opposite flow but no specific line is constructed. The third phenomenon, named dynamic lane formation is the situation in which the interaction of opposite flows results in formation of lanes [Blue and Adler, 2001]. Blue and Adler have also modeled multidirectional flows and concluded that multidiectional flows could not be modeled using bidirectional models [Blue and Adler, 2000].

2. Purpose and Methodology

In conventional manuals of design, effects of multidirectionality on capacity and level of service in pedestrian facilities are implicitly neglected. In this paper, the validity of this assumption is evaluated. This paper investigates the effects of multidirectionality on the main parameters of pedestrian flow. As evident in the introduction section of this paper, previous studies have yielded contradictory results about effect of multidirectionality which may be due to the diversity of location and social context of each study. This marks the importance of local studies on pedestrian flow behavior.

This paper investigates two opposing pedestrian flows. Data was partly gathered by means of a controlled experiment and partly from direct videotaping of pedestrian flow in urban walkways. The controlled experiment was conducted in a corridor within the department of transportation engineering of Isfahan University of Technology. As shown in figure 1, the environment of the experiment was an isolated rectangular corridor of length 9 (m) and width

2.85 (m). Population under observation included male and female students. At each stage of the experiment, volunteers were divided in two groups with intended population and were asked to walk normally along the corridor. In order to observe the effect of relative flow, two directional ration including one-to-one (50-50) and two-to-one (70-30) were established in the experiment. This ration would yield densities approximately at the borders of Highway Capacity Manual (HCM 2010) level of service. The movement of volunteers was videotaped and later the speed and traversal times were extracted for every person.

Figure.1.The overview of experiment location

The videotaping of pedestrian walkways was carried out in a uniform segment of a walkway located in central part of Isfahan. The segment was not influenced by intersections. Density was calculated by dividing the number of people in the frame by its area. Flow rate was calculated by dividing the number of people entering the segment within a time interval by the width of the segment and the length of the time interval.

Figure 2. The overview of pedestrian walkway

3. Analysis

The fundamental theory assessed in this paper is that the behavior of flow is different under uni and bidirectional regimes. The behavior is stated in terms of main parameters of flow including density, flow rate, and speed. To evaluate this statement, data collected from the experiment and direct observation were analyzed and the behavior of the minority, the majority, and lane formation was investigated. Moreover, the effect of directional ratio on speed, comparison of fundamental diagrams, and entropy of speed under two regimes were conducted and are discussed in the following sections.

3.1 Effect of Directional Ratio on Speed

In order to witness the difference of uni and bidirectional regimes, mean pedestrian speed in different densities was plotted. Figure 3 shows the plot. It could be witnessed that points of two regimes do not coincide. This might show that two regimes are not identical. To probe more deeply, difference of mean speed for same density under two regimes is shown in figure 4.

Positive values in figure 4 indicate that speed in bidirectional regime is higher that the speed in unidirectional regime at same density. This could indicate that the effect of congestion in the same direction on the speed is more than the effect of opposite flow. Higher speeds in bidirectional flow results in higher flow rate i. e. the total flow of both directions in the bidirectional regime is higher than the flow rate under unidirectional regime. This does not agree with what Kretz et al. (2006) observed.
Figure 5 shows the relative difference between two regimes in different densities. It could be observed that as the density increases, the relative speed difference among two regimes also increases. Up to density 0.6 person/m^2 speeds are almost similar (differences are less than 10%) but for higher densities, the difference is evident.

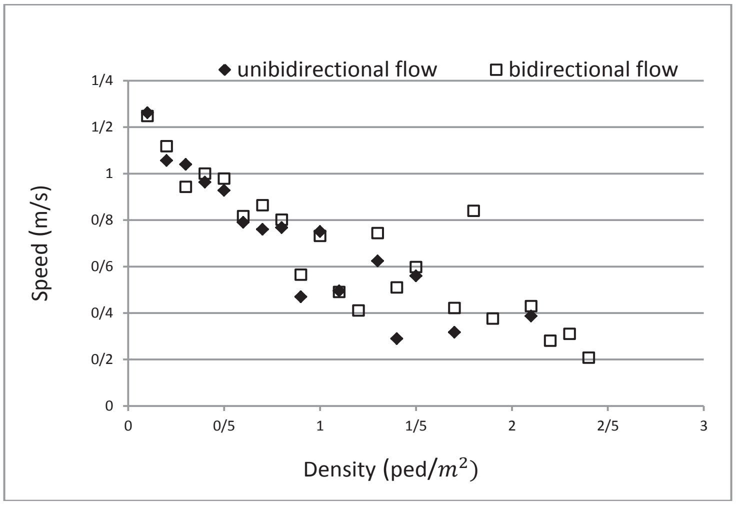

Figure 3. Speed-density data

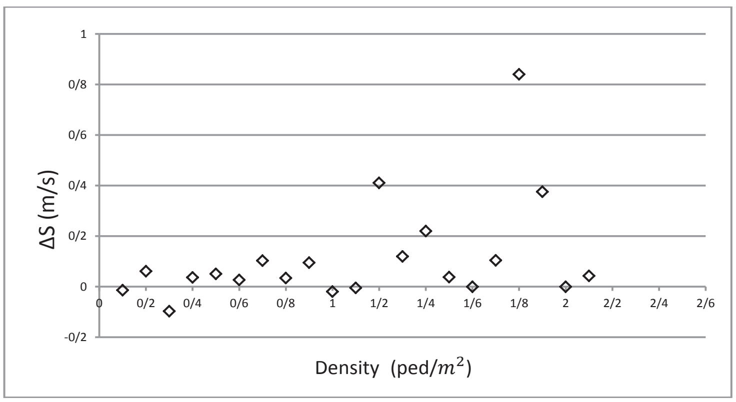

Figure 4. Mean speed difference -density data

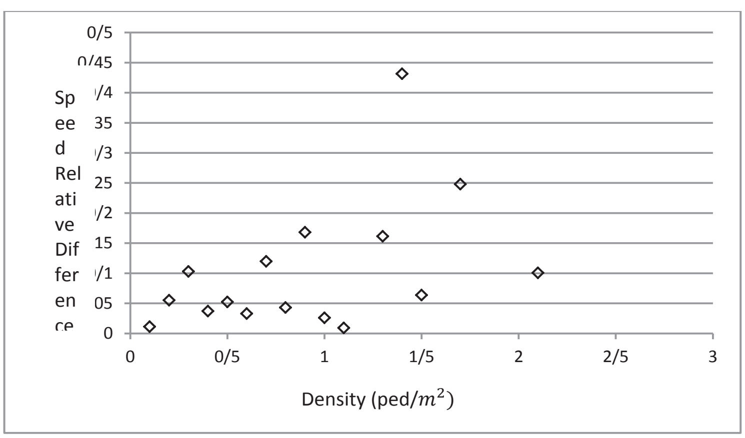

Figure 5. Speed relative difference -density data

3.2 Effect of Bidirectionality on Majority and Minority

So far it was established that bidirectionality does have effects on pedestrian speed. In order to derive more details on speed of the majority and minority streams, values are presented in table 1.

Table 1. Mean speed of minority and majority groups in unequal bidirectional flow

mean speed of the majority (m/s)	mean speed of minority (m/s)	Density (ped/m^2)
1.22	1.42	0.16
1.21	1.27	0.23
1.15	1.18	0.43
1.07	1.09	0.70
1.01	1.08	1.13

Values of speed show that at each level of density, mean speed of the majority is higher than the mean speed of minority. This indicates that the effect of the density of pedestrians moving along the same direction has greater effect on one's speed than those opposing her. This in turn could be because of a kind of imposed order in the majority. Higher density of the majority makes them move more close to each other and have less free space. Therefore their surface of contact with the opposing stream is minor. This conclusion is in accordance with what Flötteröd and Lämmel found and contradictory with the conclusion of Kretz et al.

4. Lane Formation

It is observed in various studies that pedestrians walking in same direction tend to move in a queue. This phenomenon is called lane formation. Although speed adaptation with the preceding person may be undesirable, it is more tolerable than confronting others every now and then. Therefore lane formation is observed in bidirectional flows more evidently. Moreover, lane formation is more likely in higher densities. Detecting lanes is also more difficult in sparse populations [Teknomo, 2002].

In the experiment, detecting lanes for population lower than 11 was not possible. Figure 6 shows a frame of the experiment with population equal to 11.

Figure 6. The overview of experiment location with 11 participants

Shape of lane formed in populations equal to 18 and 34 were not the same. Figure 7 shows the lanes in both populations and table 2 presents the number of lanes for each population and regime.

Figure 7.a) Snapshots for the run with N = 18 b) Snapshots for the run with N = 34

Table 2. The Number of formed lanes in different densities and regims

number of lanes	directional ratio	Number of participants
4	unidirectional	18
5	bidirectional	18
4	unidirectional	34
6	bidirectional	34

Number of lanes in bidirectional regime at each density is higher than unidirectional. As the population increases from 18 to 34 and therefore density from 0.7 to 1.35 person/m^2 nothing happens to the number of lanes. Therefore it could be concluded that effect of bidirectionality on lane formation is more than the density.

4.1 Comparison of Fundamental Diagrams

Fundamental diagrams were plotted using the collected data for uni and bidirectional regimes. The best fits of both regimes are shown in table 3.

The best fit for describing the mutual behavior of speed and density in unidirectional and bidirectional regime was logarithmic function and exponential function respectively. This shows the effect of bidirectionality on the behavior of the flow where unidirectional curve stabds higher than the bidirectional curve. For densities in the range of 0.3 and 1 person/m^2, two curves almost coincide but with the increase of density, they come apart. Both diagrams are presented in figure 8.

Table 4 shows the best fit of density-flow data. For both regimes, power function is the best fit but its parameters differ under uni and bidirectional stream. Plots are illustrated in figure 11 and values are presented in table 4. Figure 11 shows that by increasing the density, the difference among two regimes becomes more apparent.

Table 3. the relation between density and speed in unidirectional and bidirectional stream

F	R^2	equation	stream
111	0.5	$S = 0.674 - 0.266\text{Ln}(D)$	unidirectional
121	0.44	$S = 1.164e^{-0.578D}$	bidirectional

Table 4. The relation between density and flow in unidirectional and bidirectional stream

F	R^2	equation	stream
372	0.77	$Q = 0.623D^{0.659}$	unidirectional
261	0.63	$Q = 0.613D^{0.620}$	bidirectional

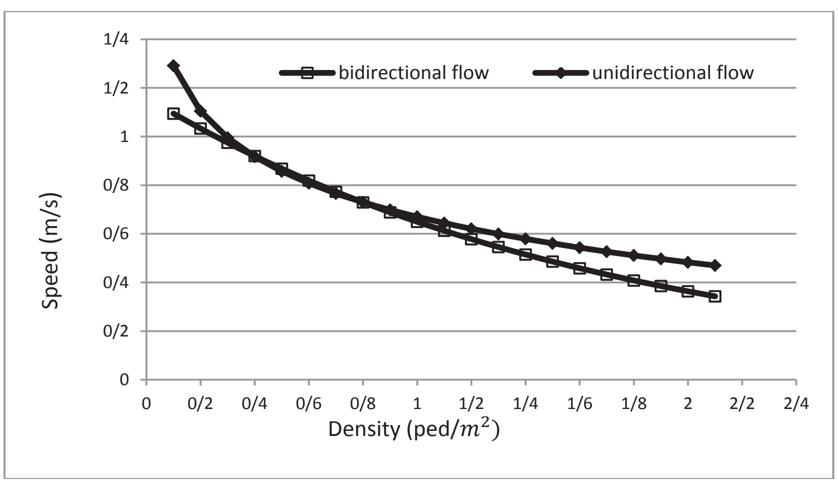

Figure 8. Speed-Dendity diagram in unidirectional and bidirectional stream

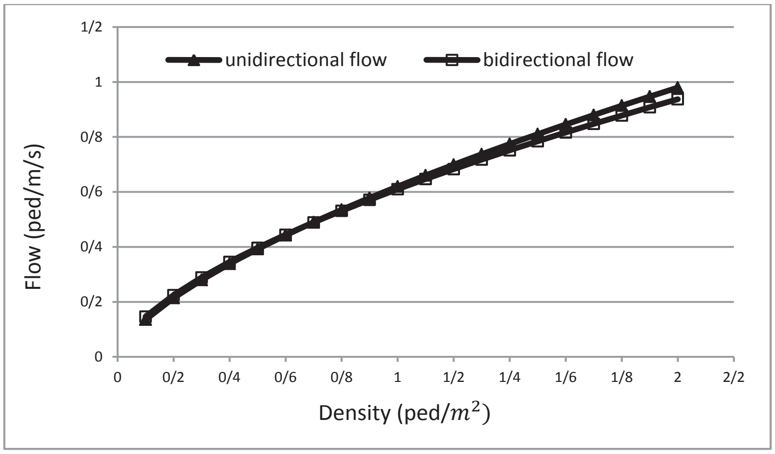

Figure 11. Flow-Density diagram in unidirectional and bidirectional stream

4.2 Speed Entropy

Entropy is a measure for describing the uncertainty of a system. Higher values of entropy indicate more uncertainty and disorder. Entropy is calculated by equation (1)

$$E = -\sum_{i} p_i \ln p_i \quad (1)$$

Values of entropy in various land uses are presented in table 5. Results show that entropy is higher under unidirectional regime. The reason is that under bidirectional regime, freedom of pedestrians is less and they try to refuge to their stream.

Table 5. Values of entropy in various land uses

entropy	Directional ratio	Land use
2.33	unidirectional	religious
2.24	bidirectional	religious
2.46	unidirectional	leisure
2.43	bidirectional	leisure
2.18	unidirectional	educational
1.97	bidirectional	educational

5. Conclusions

Analysis of this paper showed that unlike the implicit assumption of conventional transportation manuals, multidirectionality does have significant effect on the behavior of pedestrian flow. Quantitative presentation of the results lets the planners to evaluate the amount of influence of bidirectionality of the stream and compensate for the shortcoming of conventional manuals. Findings of the paper about the main parameters of flow are listed below:

1. The best fitted speed-density curve is logarithmic and exponential for uni and bidirectional flows respectively. Therefore the effect of density on speed is greater under bidirectional flow. The best fitted flow-density curve is power function for both regimes but the parameters of the functions indicate that the effect of density on flow rate is greater under bidirectional regime.
2. In all levels of density, the mean speed in bidirectional regime is higher than unidirectional. Increasing the density increases the difference especially at densities higher than 0.6 person/m^2.
3. Density of the stream along the pedestrian's direction has more effect on her speed compared to the opposing flow.
4. In densities lower than 0.43 person/m^2, no lane formation was observed. As the density increase, people tend to follow their preceding person instead of confronting the opposing flow. Therefore, it could be prescribe that in high densities implementation of policies that organizes the crowd could be of great contribution to movement.
5. Dispersion of density-flow date points in bidirectional regime was higher than unidirectional which implies the higher diversity of bidirectional flow. Moreover, the entropy of unidirectional flow was higher than

bidirectional which indicates of more disorder in bidirectional flow. The reason may be that in bidirectional regime, freedom of pedestrians is less and also that pedestrians seek some kind of protection in their stream.

6. Number of formed lanes in bidirectional flow was higher than unidirectional flow under all density levels. Increasing the density did not change the number of lanes.

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